Overall blackout risk and cascading failure

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Detailed postmortem analysis of a particular blackout

- arduous (months of simulation and analysis) but very useful
- a basis for strengthening weak parts of system
- motivates good practice in reliability: “Blackouts cause reliability”

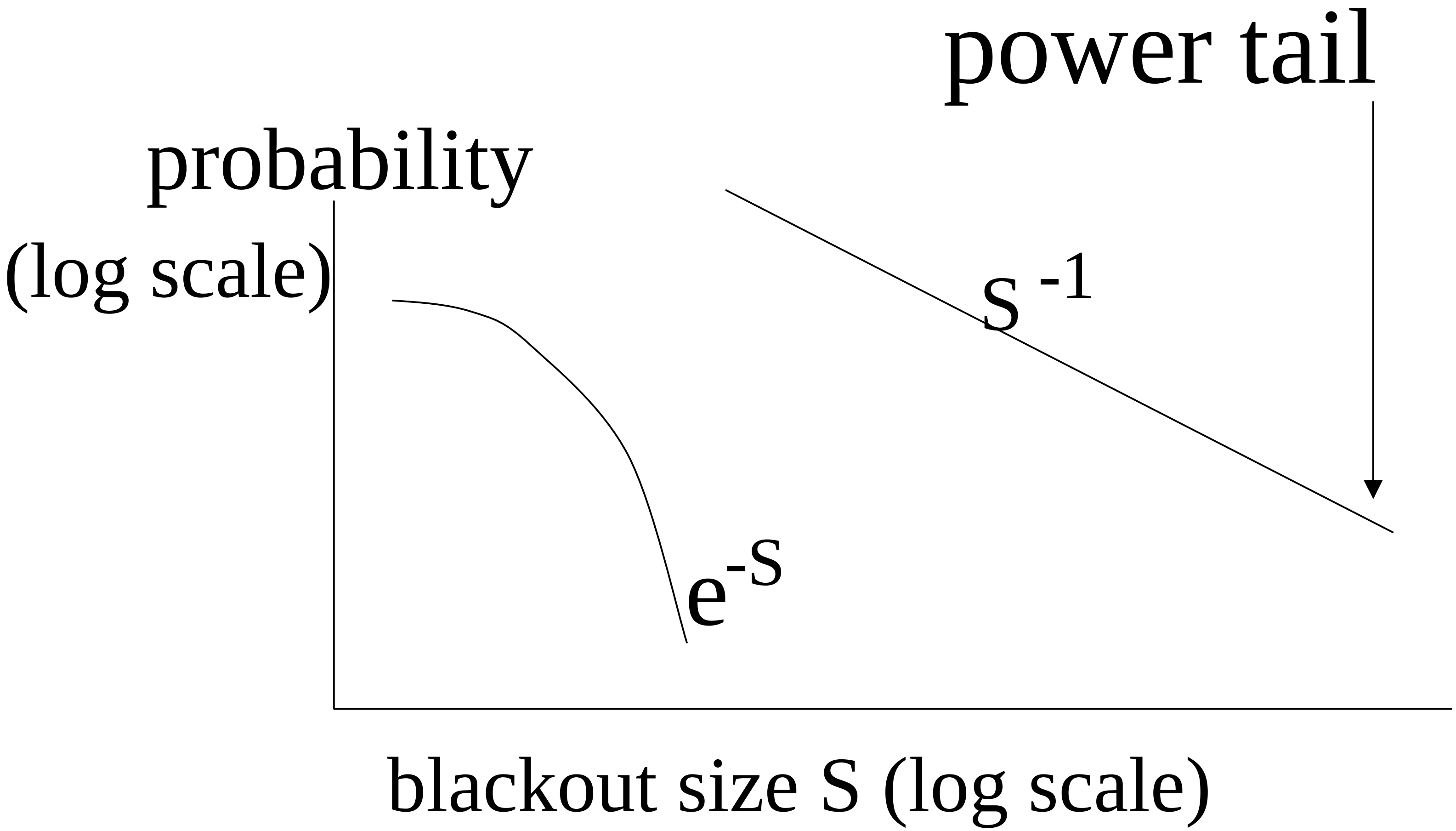
General approach

- Instead of looking at the details of individual blackouts, look at overall risk of blackouts
- Global top-down analysis; look at bulk system statistical properties.
- Complementary to detailed analysis

Blackout risk as size increases

risk = probability x cost

- Cost increases with blackout size.
  example: direct cost proportional to size
- How does blackout probability decrease as size increases? … a crucial consideration for blackout risk!

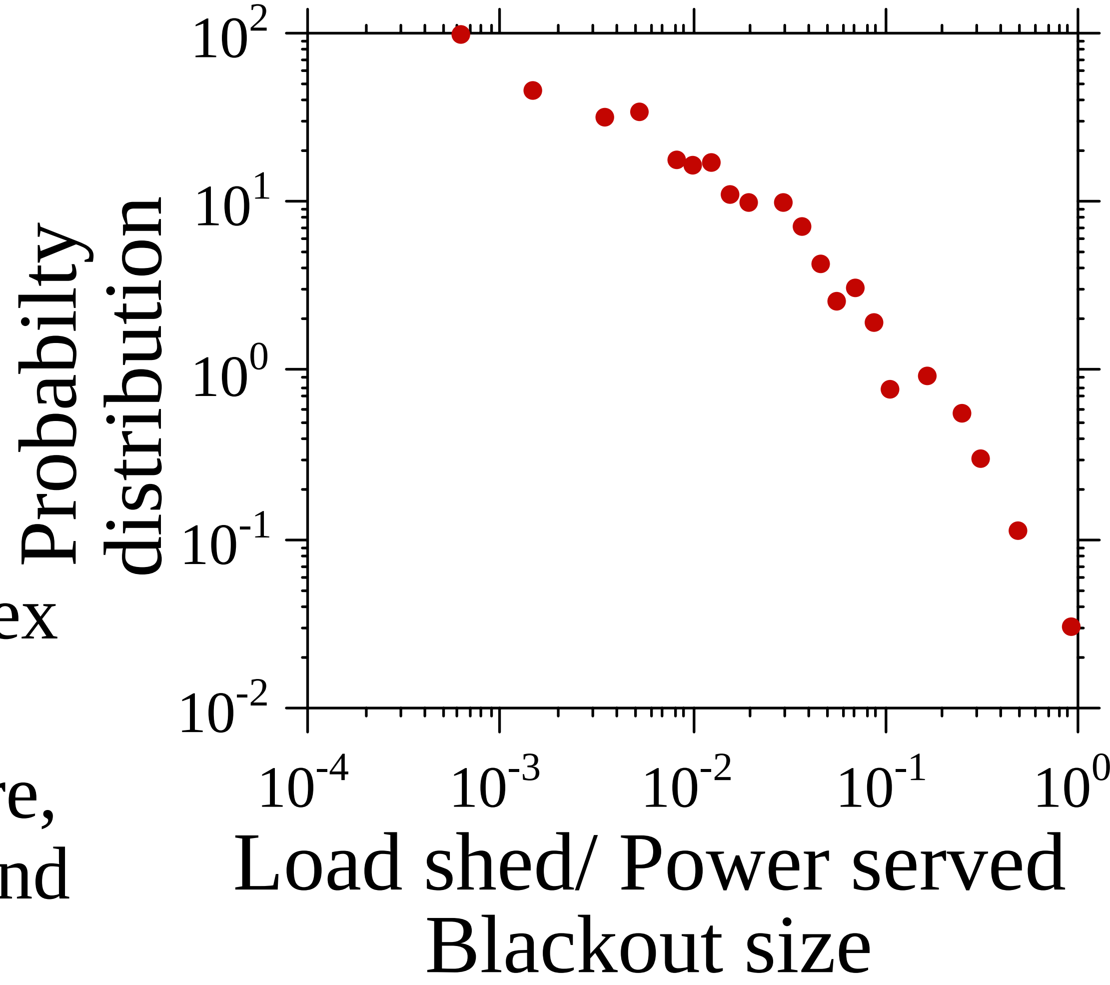


power tails have huge impact
on large blackout risk.

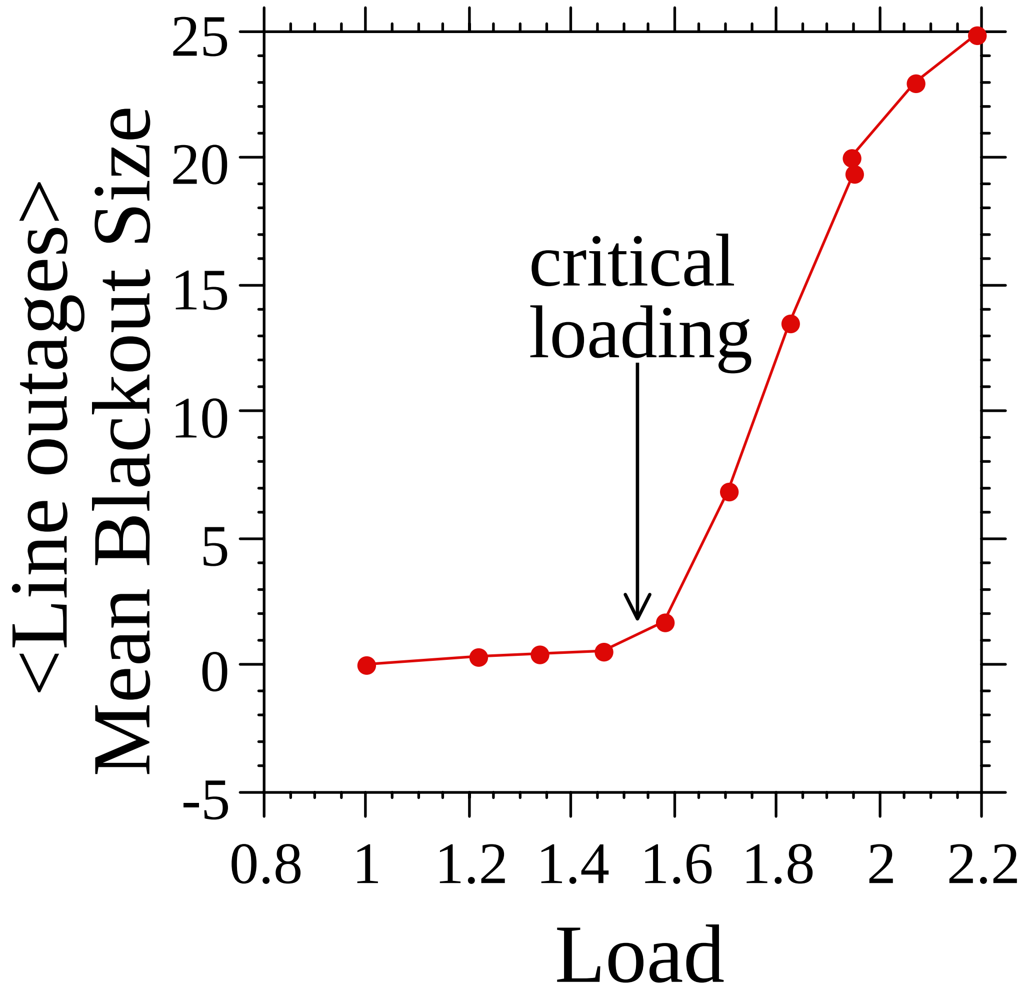
risk = probability x cost

NERC blackout data shows power tail

- Large blackouts more likely than expected
- Conventional risk analysis tools do not apply; new approaches needed
- Consistent with complex system near criticality
- Large blackouts are rare, but have high impact and significant risk



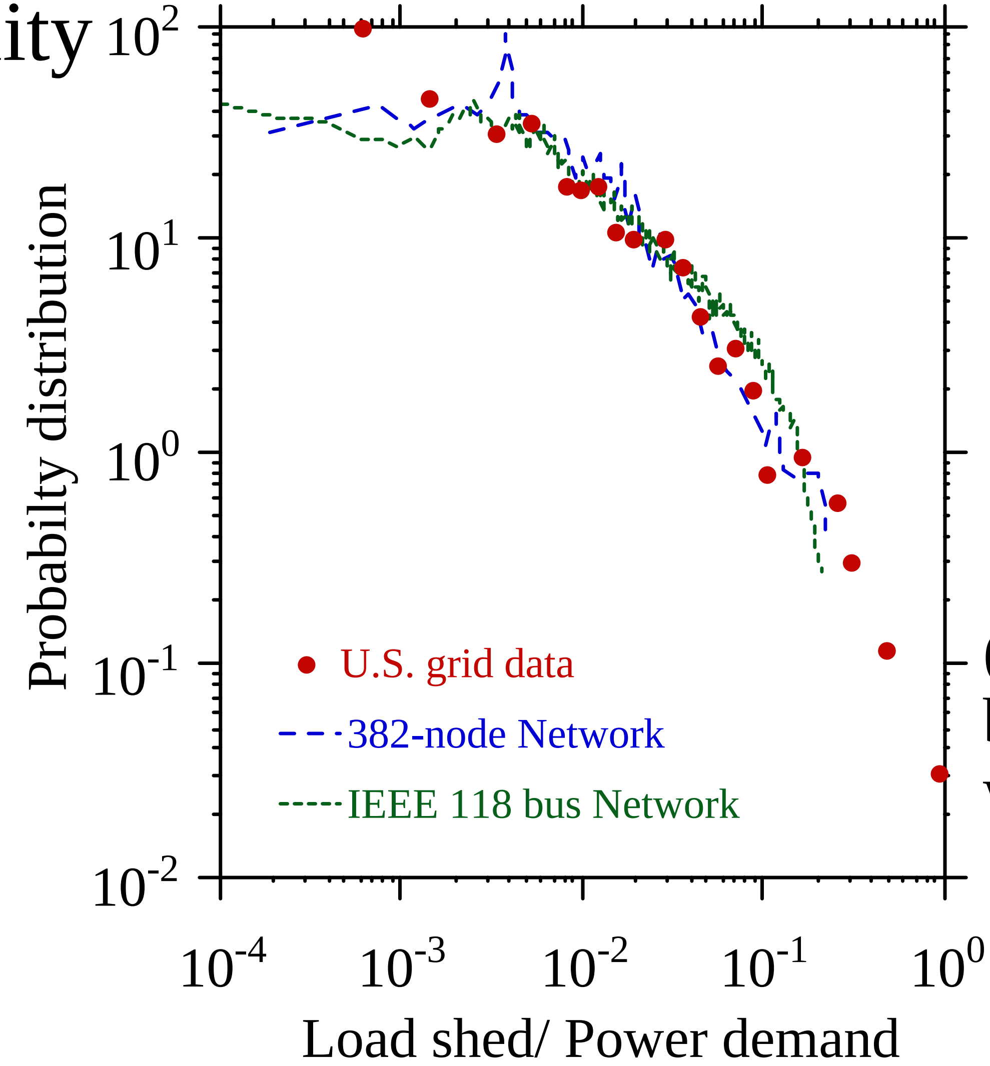
Critical loading in OPA blackout model



Mean blackout size sharply increases at critical loading; increased risk of cascading failure.

OPA blackout model can match NERC data

probability



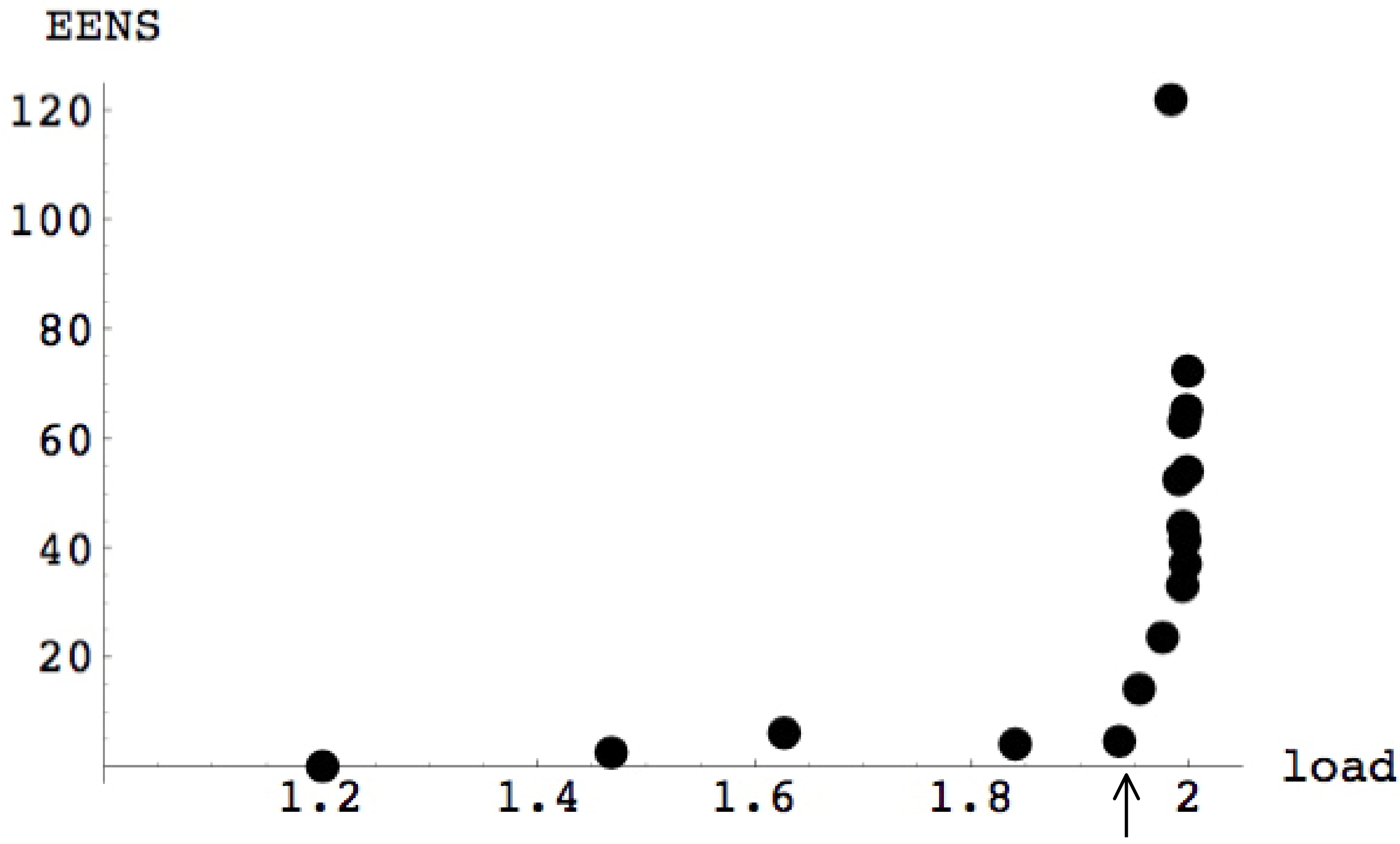
(August 14 2003 blackout is consistent with this power tail)

blackout size

Blackout size as load increases. Manchester model

(Nedic, Dobson, Kirschen, Carreras, Lynch, PSCC August 2005)

EXPECTED ENERGY NOT SERVED

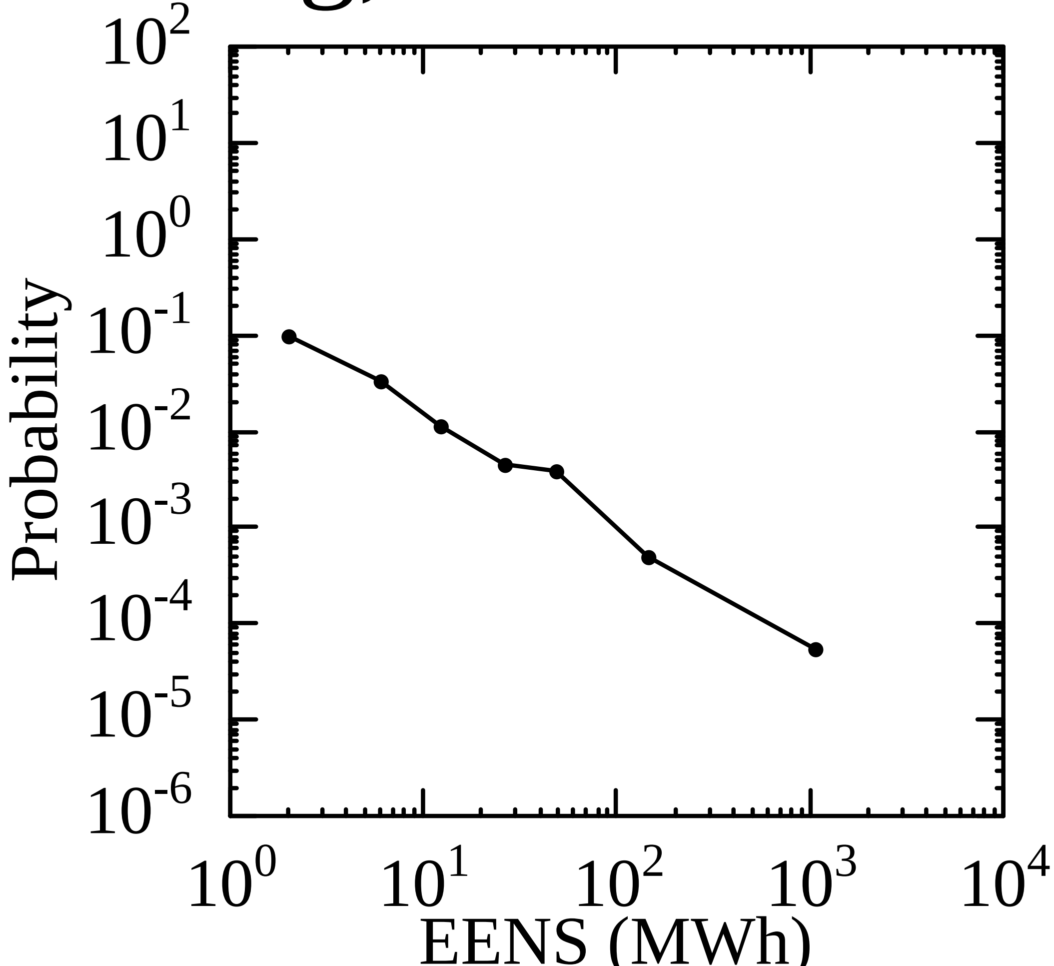


LOAD

critical load

Distribution of blackout size at critical loading; Manchester model

probability
density
(log scale)



blackout size (log scale)

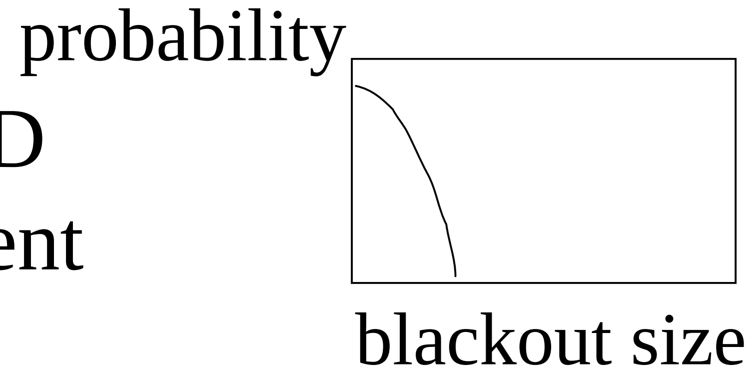
Cascading failure depends on loading

Mechanisms of cascading failure include:
hidden failures, overloads, oscillations, transients, control or operator error, ...

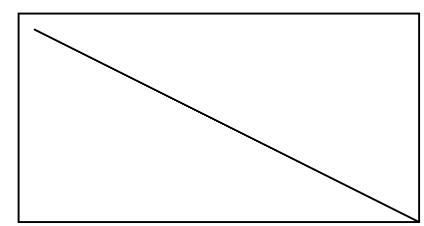
All depend on loading

Effect of Loading

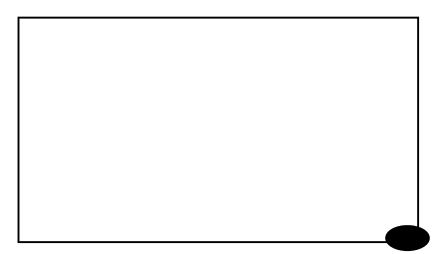
log log plots



- VERY LOW LOAD
  - failures independent
  - exponential tails



- CRITICAL LOAD
  - power tails



- VERY HIGH LOAD
  - total blackout likely

Significance of criticality

- At critical loading there is a power tail, sharp increase in mean blackout size, and an increased risk of cascading failure.
- Criticality gives a power system limit with respect to cascading failure.
- How do we practically monitor or measure margin to criticality?

Ongoing research on margin to criticality

- One approach is to increase loading in blackout simulation until average blackout size increases.
- Another approach is to monitor or measure how much failures propagate (λ) from real or simulated data.

λ controls failure propagation

- Subcritical case $\lambda<1$:
  failures die out
- Critical case $\lambda=1$:
  probability distribution of total number of failures has power tail
- Supercritical case $\lambda>1$:
  failures can proceed to system size

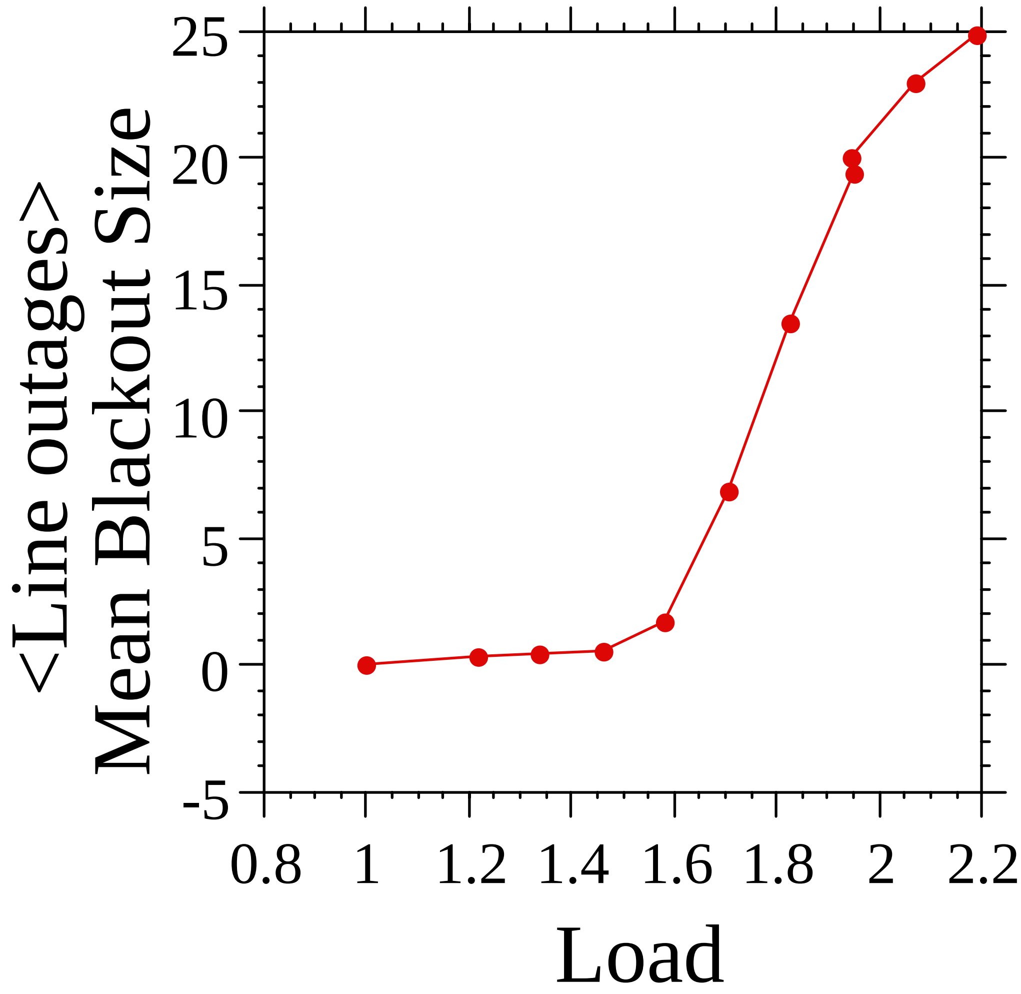
Context

- We suggest adding an “increased risk of cascading failure” limit to usual power system operating limits such as thermal, voltage, transient stability etc.
- Cascading failure limit measures overall system stress in terms of how failures propagate once started; complementary to inhibiting start of cascade with n-1, n-2 criterion.

Power systems not static: they slowly evolve subject to strong societal and economic forces of loading increase and system upgrade

- 2% annual load increase in North America
- Blackouts cause upgrades. (continual upgrading is an essential and necessary process)

An explanation of power system operating near criticality



Mean blackout size sharply increases at critical loading; increased risk of cascading failure.

Strong economic and engineering forces drive system to near critical loading

High loading versus reliability

- What is the correct balance?
- Is near critical loading desirable?

NEED TO ESTIMATE OVERALL BLACKOUT RISK

Risk-based approach requires:

- cost of blackouts as function of size
- probability of blackouts as a function of size
- new methods to monitor and quantify this risk

How do we manage blackout risk?

- *Formulate* problem as jointly reducing small, medium, and large blackout frequency (e.g., avoid suppressing small blackouts at the expense of increasing large blackouts).
- *Solve* problem by
  - continuing to upgrade system
  - limit cascades starting and propagating
  - develop tools to quantify and monitor overall blackout risk

For more information see papers at
http://eceserv0.ece.wisc.edu/~dobson/home.html

[EXTRA SLIDES FOLLOW]

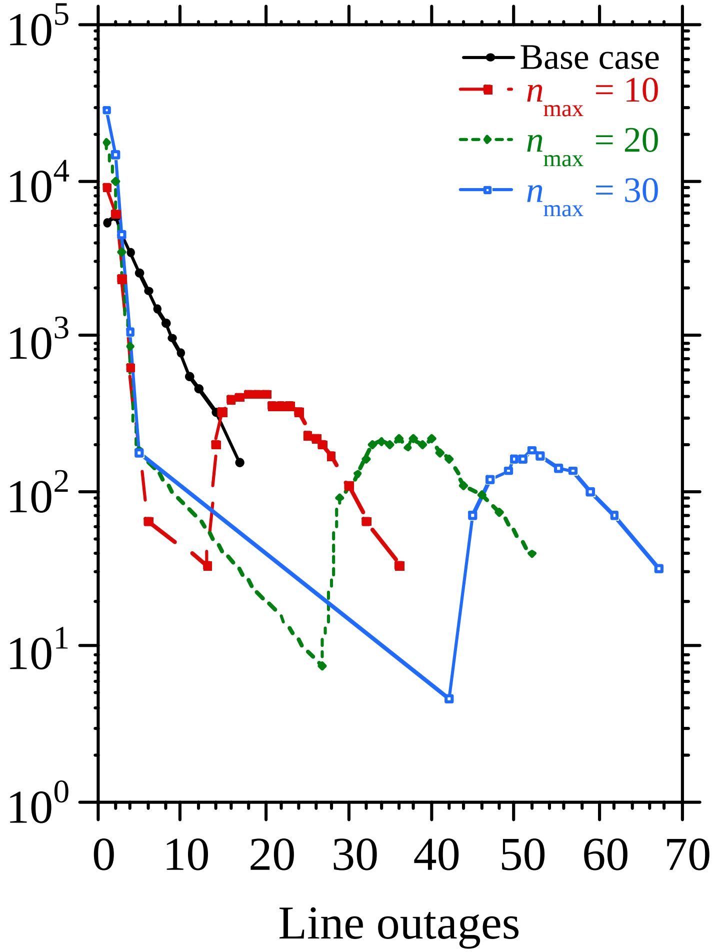
Abstract of talk: We discuss the overall risk of blackouts of various sizes based on NERC data and simulations of cascading failure. There is evidence of a critical loading at which the mean blackout size sharply increases. While mitigation to reduce the chance of initial failures is important and valuable, it is also useful to consider reducing the extent to which failures propagate after they are initiated.New methods to monitor failure propagation are emerging. The problem of mitigating blackouts can be framed as jointly reducing the frequency of small, medium and large blackouts so as to manage the overall blackout risk. The interplay between reliability and overall system loading and upgrade is strongly driven by economic, societal and engineering forces.

Effect of risk mitigation methods on probability distribution of failure size

"obvious" methods can have counterintuitive effects in complex systems

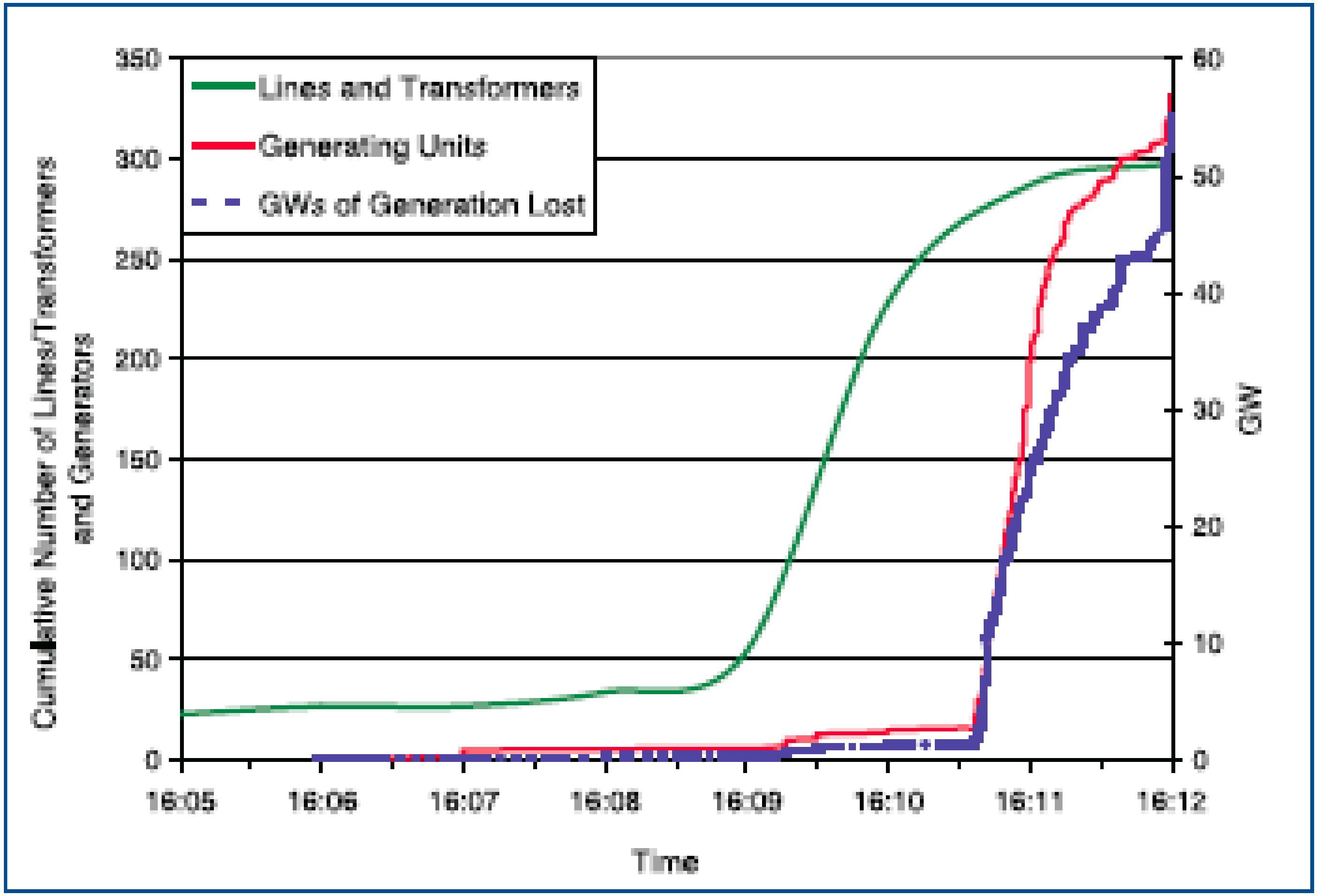
A minimum number of line overloads before any line outages

- With no mitigation, there are blackouts with line outages ranging from zero up to 20.
- When we suppress outages unless there are $n > n_{max}$ overloaded lines, there is an increase in the number of large blackouts.
- The overall result is only a reduction of 15% of the total number of blackouts.
- this reduction may not yield overall benefit to consumers.



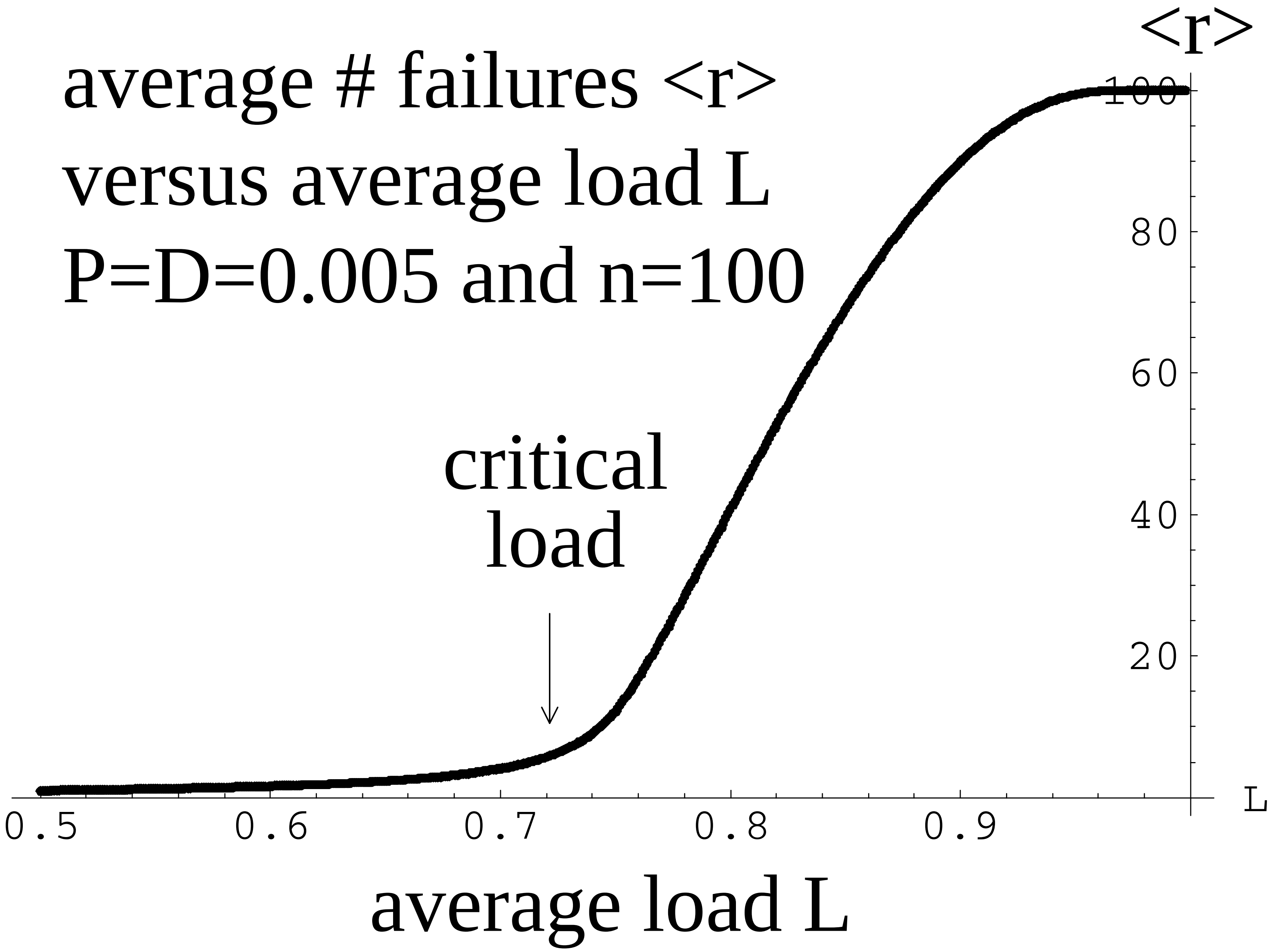
Cumulative Line Trips from August 2003 Blackout Final Report

Figure 6.1. Rate of Line and Generator Trips During the Cascade



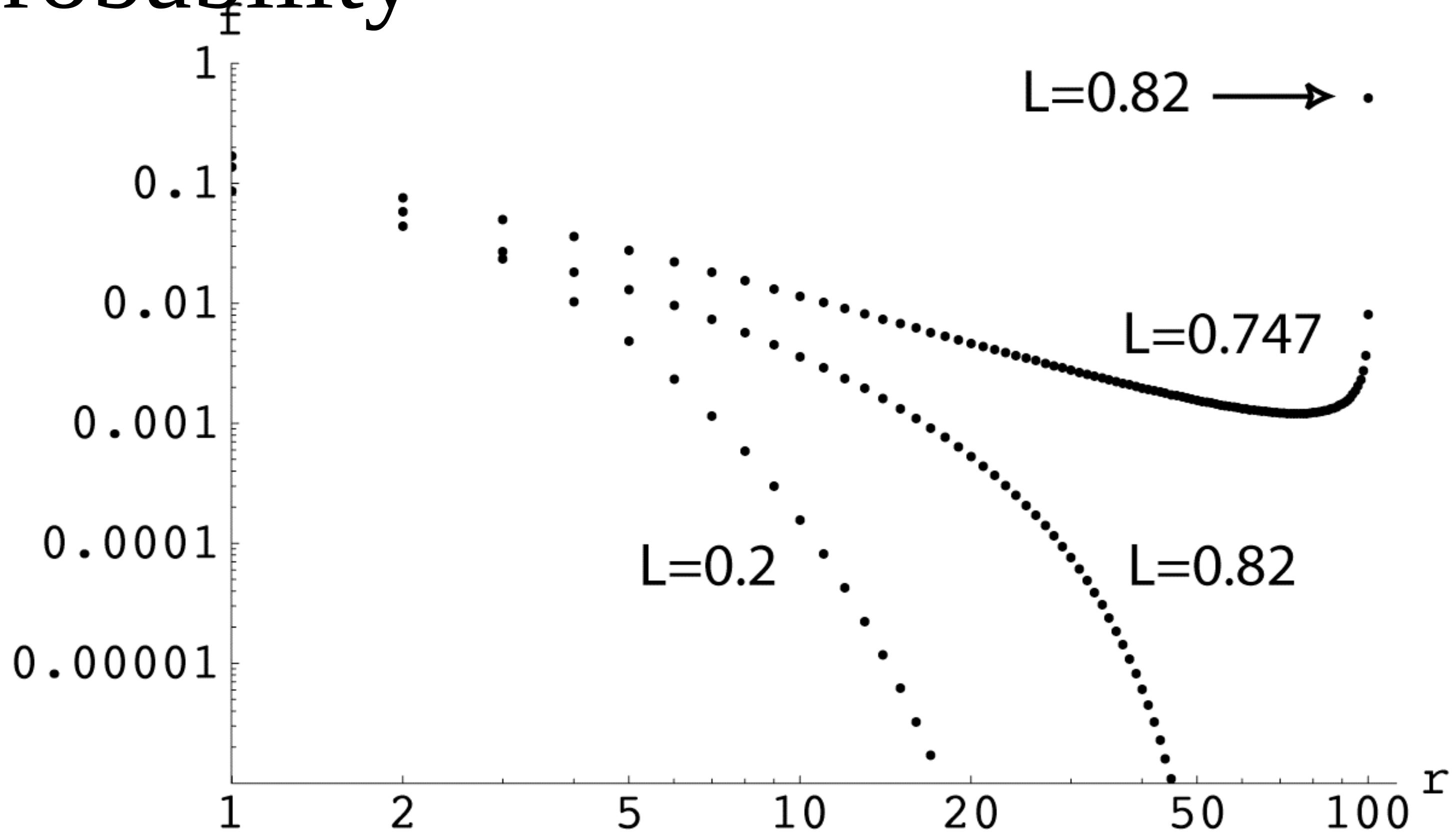
CASCADE model

- Probabilistic loading-dependent model of cascading failure --- captures system weakening as successive failures occur
- Captures some salient features of generic cascading failure in an analytically tractable model.
- Key output is number of failed components

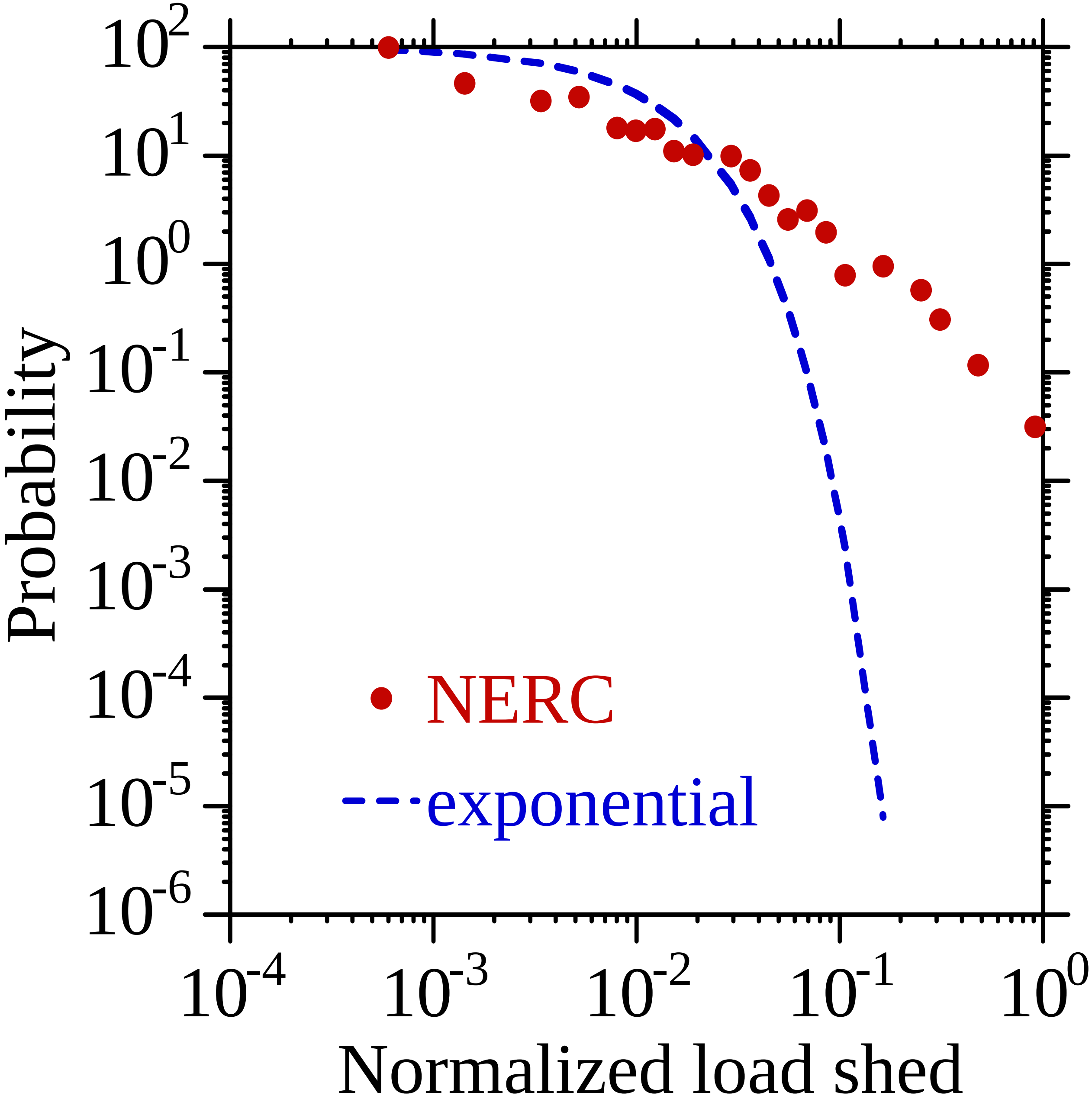

average # failures <r>
versus average load L
P=D=0.005 and n=100
critical
load
<r>
100
80
60
40
20
L
0.5
0.6
0.7
0.8
0.9
average load L

probability distribution as average load L increases

probability

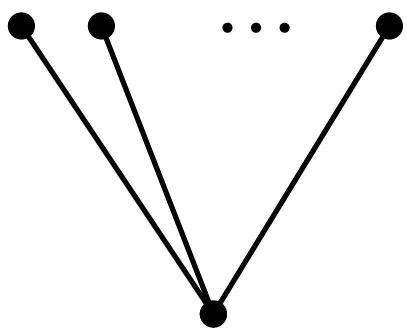


number of failures



NERC distribution of blackout size and an exponential distribution on a log-log plot

Branching from one failure

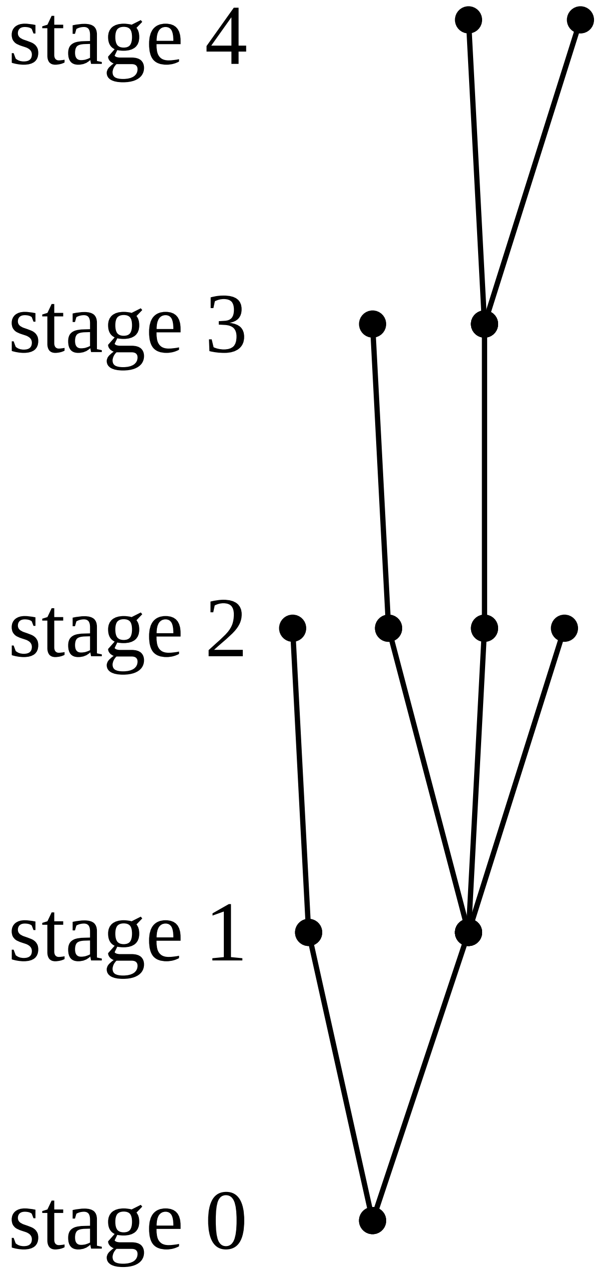


offspring failures

a failure

number of offspring ~ Poisson(λ)

mean number of failures = λ



Branching Process

– each failure independently has random number of offspring in next stage according to Poisson(λ)

– **λ = mean number failures per previous stage failure**

– λ^k = mean number of failures in stage k